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INTEGRATED MEMBRANE FEED STREAM PERFORMANCE IMPROVEMENT-A REVIEW

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ABSTRACT

Integrated membrane system has become a promising technique for oil-water waste separation in recent years, compared to the traditional membrane technology. The integrated membrane system is considered the superior technology for oil-water waste separation, due to the high oil-water separation efficiency it offers. However, the feed stream of the integrated membrane system experiences extensive pores blockage (membrane fouling) which hampers the oil-water separation efficiency. Membrane fouling during oil-water separation leads to poor membrane performance, such as permeate flux decline and poor rejection factor. Several techniques have been considered to minimize the membrane fouling to optimize the performance of the integrated membrane feed stream. Such as the optimization of the operating parameters, operating conditions in the integrated membrane feed stream and employing different experimental setups. This review covers the two critical factors which are commonly considered during the optimization of the integrated membrane feed stream i.e., operating parameters and operating condition theoretical models in relation to the experimental setup analysis for optimal performance of the integrated membrane feed stream. The critical factors are discussed, compared, and the limitations on the theoretical models are presented accordingly. Despite all the limitations presented by the integrated membrane system is still considered the superior oil-water separation technology, such that the UF-FO-MD integrated membrane feed stream obtained a high oil-water separation efficiency at low costs during the experimental analysis, using the developed theoretical models.

KEYWORDS: Feed Stream; Oil-Water Waste; Separation & Integrated Membrane

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Original Article

1. INTRODUCTION

Oil-water waste forms a part of the extensive waste pour produced in food, chemicals, gas, petroleum, and oil industries (Bolto et al., 2020). The oil-water waste capacity is frequently increasing due to the growth of oil-water producing industries daily. The oil-water waste generally contains the compound mixture of dispersed and dissolved oil. The chemical and material properties of oil-water waste produced from different industries vary depending on the location (Hubadillah et al., 2018; Rong et al., 2018). the highest temperature of the oil-water waste ranges between 40 ºC to 80 ºC, if oil-water waste is not properly treated it may cause serious harm to humans, the environment, and ecology (Salama, Ibrahim, et al., 2018). The oil-water waste may cause water pollution, affect the soil, and form a harmful chemical compound (Biniaz et al., 2019; C. Li et al., 2020; J. Li et al., 2018). To date, the oil-water waste remains a great challenge facing the food, petrochemical, and oil industries which requires the

proper treatment to meet the discharge requirements (W. Liu et al., 2020).

There are various existing techniques developed for the separation of oil-water waste such as skimming, particles settling and gravitational separation of water from oil methods (Kalla, 2021; W. Liu et al., 2020; Salama, 2018c; Salama, Zoubeik, et al., 2018; Z. Zhang et al., 2019). However, these methods are more efficient in treating disseminated oil but show exceptional inadequacy during the oil-water separation when oil has a small diameter size(Wei et al., 2018). The existing traditional processes for separating oil-water waste showed limitations in meeting the strict discharging requirements (e.g., oil contents < 10 mg/L and suspended solids (SS) < 10 mg/L) (Applications et al.,2017). To address the limitations faced by membrane technology during oil-water separation, the integrated membrane system is recommended to be a promising membrane technology for the effective oil-water separation process (Yi Liu et al., 2020). Due to its benefits such as high filtration capacity and uniform permeate quality compared to traditional processes (Tanudjaja et al., 2019). The integrated membrane system is elaborated as a combination of different independent units (membranes) with features to meet the optimal oil-water separation efficiency over a single membrane performance (Zhao et al., 2020).

The most used integrated membrane system for oil-water separation is Microfiltration (MF), Ultrafiltration (UF), Reverse Osmosis (RO), and Membrane Distillation (MD), these systems are more efficient for oil-water separation (Qin et al., 2019; J. Zhu & Jin, 2017). The ceramic ultrafiltration (UF) was largely investigated for oil-water waste separation and it was found to be superior to the polymeric membrane, due to its longer life span, robust and higher stability (Han et al., 2019). However, it was found that when the feed stream supporting layer of the forward osmosis (FO) and membrane distillation active layer (MD) in the integrated membrane system becomes directly in contact with oil-water it can cause high membrane fouling which hampers the performance of the membranes (He et al., 2017; Rahimzadeh et al., 2016; S. Zhang et al., 2018). To date, membrane fouling is considered the major problem in the feed stream of integrated membrane system which affects the oil-water separation process negatively by blocking the membrane pores to reduce the permeate flux (Ahmad et al., 2015; Y. Li et al., 2020; Lin et al., 2019). Several investigations have been focused on reducing the effects of the integrated membrane feed stream by reviewing the effects of the design, membrane wettability, operating parameters, and operating conditions (Park et al., 2018).

To date, there is enough research evidence reviewing the feed stream of the integrated membrane system for optimal performance during the oil-water separation (B. Ma et al., 2019). The main challenges recently reported on the integrated membrane feed stream is the blockage of the pore, which is believed to be caused by the effects of poorly estimated morphology of the pore sizes, operating parameters, operating conditions, and inadequate fouling predictive models for the optimal performance of the integrated membrane feed stream during oil-water separation (Tin et al., 2017). The feed stream of the integrated membrane system is dependent on the operating parameters such as driven pressure which is elaborated as the main operating force for the oil/water filtration process, and this driving force is transmembrane pressure (TMP) (Woo et al., 2018). The influence of the parameters in the integrated membrane system is measured with respect to the permeate flux during the oil/water separation to measure their influence in the permeate rejections (Jia et al., 2018; Q. Ma et al., 2016). Therefore, the membrane performance is characterized mainly in terms of permeate flux and rejection efficiency (Choudhury et al., 2019; Tanne et al., 2019; Y. Zhu & Chen, 2017).

2. FEED STREAM FUNDAMENTALS

In the integrated membrane system (IMS) such as microfiltration (MF), Ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO), feed stream plays an important role as it is used to determine the performance of the membrane

through investigation of the membrane separation parameters, as demonstrated on figure 1 of ceramic IMS image (Y. Yu et al., 2016).

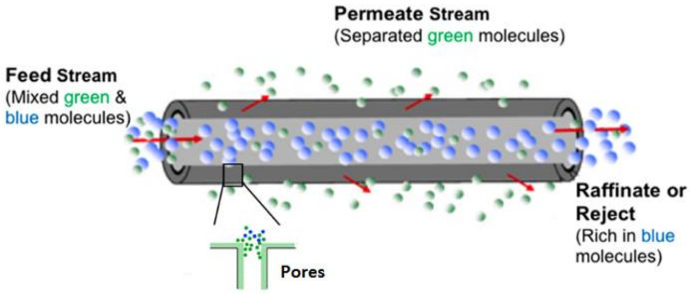

Figure 1: Schematic of Ceramic Membrane showing the Feed Stream (B. Ma et al., 2019).

The feed stream introduced in the integrated membrane system during oil-water separation is divided into retentate (which is the feed concertation passing through themembrane) and permeate (which is also known as filtration). Therefore, during the oil-water separation, the feed stream can either be permeate or retentate as demonstrated in figure 2.

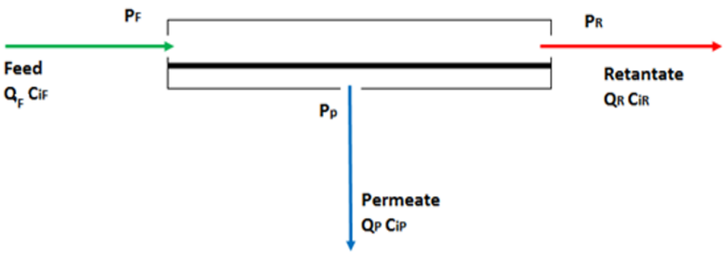

Figure 2: Schematic of Feed Stream in the Integrated Membrane System, with Key Parameters (E. Tummons et al., 2020).

In general, the feed stream of the integrated membrane system is explained by the following model (Baig et al., 2020).

$$FeedStream = Permeate + Retantate \tag{1}$$

The efficiency of the integrated membrane feed stream is measured by the oil-water rejection ratio and the permeate flux which is on the permeate side as shown in figure 2 (Liao et al., 2017). Several factors affecting the oil-water separation have been reported to be the volume flow rate of the feed stream, crossflow velocity, and driven pressure. Up to date, pore blockages (fouling) in the integrated membrane feed stream have been the major challenge that hampers the performance of the membrane during the oil-water separation (Rong et al., 2018; Tin et al., 2017). The fouling phenomenon is a complex challenge that would not be addressed by looking at one factor such as the operating conditions alone (Abid et al., 2017; Gu et al., 2018). The existing models and experimental studies developed to optimize the integrated membrane feed stream need to review and characterized according to their effectiveness towards oil-water separation (L. Yu et al., 2017). Therefore, there are several models developed to optimize the performance of the integrated membrane feed stream to improve the oil-water separation efficiency as shown in table 1.1 (Abdel-Fatah, 2018). The optimized integrated membrane feed stream could lead to a lower running cost of the oil-water filtration system and improved performance of the membrane.

Table 1: Feed Stream Models in the Integrated Membrane System

Separation Parameters	Models	Definition of Elements	References
Permeate flux	$J = \frac{Q_p}{A_e}$	Where A_e represents the surface area of the membrane	(Hubadillah et al., 2018; J. Liu et al., 2016; Ngang et al., 2017; Salama, Zoubeik, et al., 2018)
Transmembrane pressure (TMP)	$TMP = \frac{P_F P_R}{2} P_P$	Where P_F is the feed pressure (inlet), P_R is the retentate pressure (outlet) and P_P is the permeate pressure (outlet)	(Salama, 2018a; Venzke et al., 2018; Y. Zhu & Chen, 2017)
Rejection Factor	$R_i = \frac{C_{i,p}}{C_{iR}} \times 100$	$C_{i,p}$concentration of component i, at the outlet of the membrane pores and C_{iR} is the concentration in the retentate	(Guo et al., 2018; Y. Li et al., 2020)
Volume concertation ratio (VCR)	$VCR = \frac{V_{F,i} V_{F,i}}{V_{R,t} V_{F,i} V_p}$	$V_{F,i}$ represents the initial feed volume, $V_{R,t}$ is the retentate volume at time t and $V_{p,t}$ is the permeated volume at time t	(Ahmad et al., 2015; A. Huang et al., 2018; F. Zhang et al., 2016; Zuthi et al., 2017)
Transmission of Components i,	$Tr_i = \frac{C_{i,p}}{C_{iR}} \times 100$	$C_{i,p}$ concentration of component i, at the outlet of the membrane pores and C_{iR} is the concentration in the retentate	(Alkhudhiri & Hilal, 2017; Q. Ma et al., 2016; Salama, Ibrahim, et al., 2018)
Membrane selectivity between component i and j	$\frac{Tr_i}{Tr_j}$	Tr_i is the transmission component i divided by $Tr_j$is the transmission component j	(Applications et al., 2017; Brown & Bhushan, 2015; Kusworo et al., 2018)

3. EVALUATING INTEGRATED MEMBRANE FEED STREAM EFFICIENCY

The integrated membrane feed stream efficiency is defined by the oil-water rejection factor and permeates flux (S. Zhang et al., 2018). The permeate flux reduces during the oil-water separation in the integrated membrane feed stream (J. Zhang et al., 2019). This is due to both internal and surface foulants that act as an additional layer on the surface of the membrane causing the membrane resistance to the transferal of filtrate through the membrane (Lin et al., 2019). Which the permeate flux and oil-water rejection factor are influenced by the operating parameters, operating conditions, wettability, pore sizes, the morphology of the pore sizes distribution, and the effects fouling phenomenon (Han et al., 2019; Z. Zhang et al., 2019). Since The permeate flux is found to be directly proportional to transmembrane pressure, therefore it was reported to be one of the factors which have a high impact on the integrated membrane feed stream efficiency. It was reported that the transmembrane pressure must be greater than the differential osmotic pressure in the entire membrane feed stream for oil-water filtration to take place (Bolto et al., 2020; Wan et al., 2017). Therefore, the poor estimation of the operating conditions and parameters could lead to poor oil-water separation efficiency (J. Zhu & Jin, 2017).The major factor which is commonly pointed out as one which mostly hampers the efficiency of the integrated membrane feed stream is membrane pores blockage, as shown in figure 3 (fouling) (Yanan Liu et al., 2017). This fouling phenomenon can be insinuated by the poor estimation of the operating conditions, it normally affects oil-water separation efficiency in the integrated membrane feed stream (Jia et al., 2018).

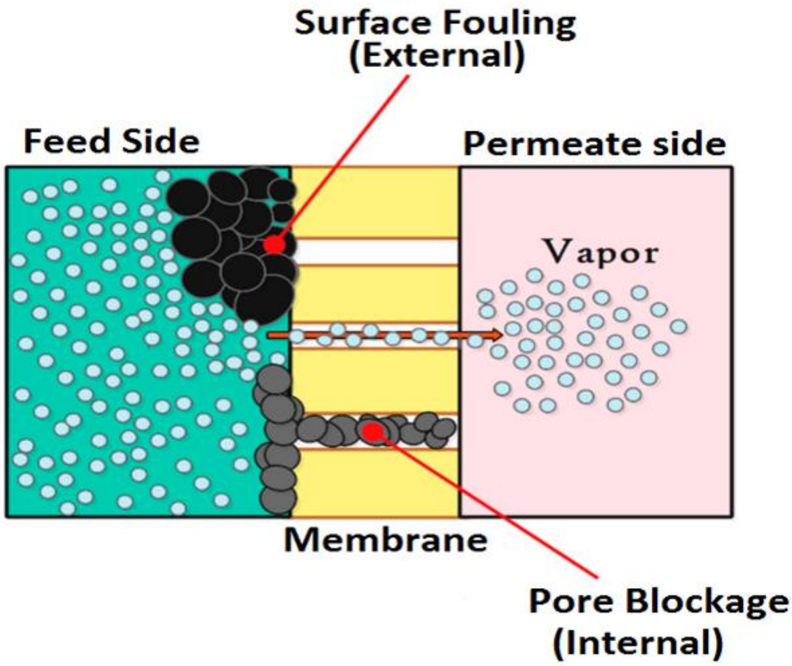

Figure 3: Demonstration of Membrane Fouling in the Integrated Membrane Feed Stream (Monfared et al., 2016).

To date, several investigations have been carried out to improve the efficiency of the integrated membrane feed stream efficiency by developing several techniques including mathematical models and experimental studies (S. Huang et al., 2018; Shirazi et al., 2016a). The common model which is used to determine the efficiency of integrated membrane feed stream is the models elaborated in equation 2 and 3, which is permeate flux and rejection ratio/factor, respectively (Borea et al., 2018; Monfared et al., 2016; Samaei et al., 2018).

$$J = \frac{TMP - \sigma \Delta \pi}{\mu (R_m + R_f)} \tag{2}$$

$$R = \frac{C_{feed} - C_{per}}{C_{feed}} \times 100 \tag{3}$$

Although there are many permeate flux models, there are other factors that also have a direct impact on integrated membrane feed stream efficiency during the oil-water separation, which needs to be taken into consideration during the analysis of the permeate flux for the optimal membrane performance. These factors which have an impact on the permeate flux are found to be the osmotic pressure differential across the membrane measured in (Pa) and permeate flux resistance due to fouling given by$R_f\,(\mathrm{m}^{-1})$, membrane resistance R_m and σ defines the reflection coefficient (Salama, 2018c). Which the rejection factor in the integrated membrane feed stream is expressed as the quality of separation, it is a ratio of permeate concentration $(\mathrm{C_{perm}})$ to feed concentration$(\mathrm{C_{feed}})$, where the separation ratio is given by $\mathrm{C_{feed}}/\mathrm{C_{per}}$ (Tanne et al., 2019).Since the efficiency of the integrated membrane feed stream is influenced by the permeate flux and oil-water rejection factor. The efforts must be made to further modify the models permeate flux and oil-water rejection factor which will be suitable for integrated membrane feed stream.

4. FACTORS AFFECTING THE INTEGRATED MEMBRANE FEED STREAM

4.1 Feed Stream Properties

During the oil-water separation, the dispersed oil droplets are pulled towards the integrated membrane feed stream surface by the permeate flux pressure, which causes the oil droplets to eventually coalesce (Wei et al., 2018). Therefore, the collection of these oil droplets on the membrane surface block the pores of the integrated membrane system (membrane fouling) and causes the permeate flux reduction (poor oil-water separation) (Choudhury et al., 2019; Salama, 2018d). Until recently, different filtration designs/techniques have been proposed to overcome/minimize the deposition of oil droplets on the surface of the membrane (Tanudjaja et al., 2019). The commonly used method is crossflow filtration i.e., the feed stream is initiated with the velocity parallel to the surface of the membrane (Qin et al., 2019; Zhao et al., 2020). The crossflow facilitates were aimed to detach the coalesced oil droplets away from the IMS surface by creating the shear stress on the walls of the membrane (Raza et al., 2019). For example, such as baffles to trigger turbulence at the surface of the integrated membrane feed stream to develop dislodging of the stuck oil droplets (Lu et al., 2018).

Even though the crossflow method was largely employed in the oil-water separation process, however, it shows its limitations in dislodging the permeating oil droplet away from the surface (Elhady et al., 2020). Since the permeating oil droplets are tiny in size (in microns or lesser), they are therefore detected on the boundary layer region (Qin et al., 2019). Where feed stream applied velocity is small. Such that the force of the shared stress applied on oil droplets on the surface of the integrated membrane feed stream may be insufficient to vacuum small oil droplets off (Ebrahimi et al., 2020). In summary, the crossflow zone in the currently integrated membrane feed stream design showed the limitation of being insufficient to sweep off the deposited oil droplets on the surface of the membrane. Which this incapability leads to membrane pores blockage (membrane fouling) and poor oil-water separation (permeate reduction).

4.2 Membrane Fouling in the Integrated Membrane System

In general, integrated membrane feed stream fouling is a complex interconnection between the solution of the feed flow and the surface of the membrane, which are associated with their physicochemical properties (Da Silva Biron et al., 2017; Jia et al., 2018; Salama, Zoubeik, et al., 2018). The membrane fouling is caused by some oil droplets which deposits on the membrane surface during oil-water separation as shown in figure 4 (Samanta et al., 2016). To date, the integrated membrane feed stream fouling is the major problem that causes the poor oil-water separation efficiency (Gondal et al., 2017). Therefore, to minimize the effects of fouling in the integrated membrane feed stream to improve the oil-water separation efficiency. Several investigations were carried out to improve the separation efficiency by adjusting the operating parameters rather than modifying the membrane design which may lead to downtime and execution costs (Salama et al., 2020). In summary, several investigations recommended the optimization of the operating parameters in the integrated membrane feed stream to minimize the effects of membrane fouling.

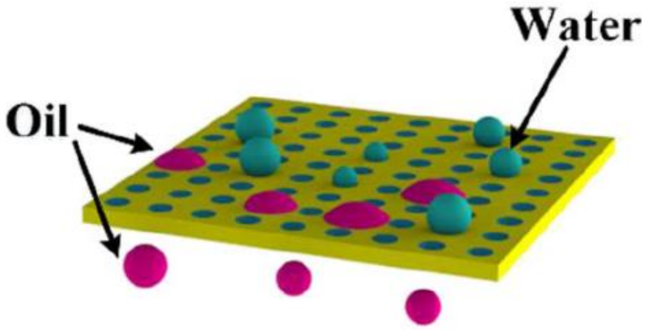

Figure 3: Demonstration of Oil-water Interaction with the Membrane Surface during the Filtration Process ***(Da Silva Biron et al., 2017)*****.**

4.3 Operating Parameters in the Integrated Membrane Feed Stream

The operating parameters that influence the performance of the integrated membrane feed stream during the oil-water separation process are found to be the feed stream flow rate, transmembrane pressure (TMP), crossflow velocity (CFV), feed temperature (T) (Jia et al., 2018; Salama, Zoubeik, et al., 2018). The influence of the parameters in the integrated membrane system is measured with respect to the permeate flux during the oil-water separation to measure their influence in the permeate rejections. Often the integrated membrane feed stream operates in one of the two techniques during the oil-water separation process, which is either the constant transmembrane pressure or constant permeate flux (Abadi et al., 2011; Geng & Chen, 2016). The selection of the suitable technique is based on the preference inspired by prior research and minimization of fouling during the separation process (E. N. Tummons et al., 2016).

Several efforts have been made to optimize the operating parameter of the integrated membrane system, such as modifying both mathematical models and experimental test rig (Hu et al., 2019; Siddiqui et al., 2016; E. N. Tummons et al., 2016). Even though there are still literature limitations showing both the relation of the integrated membrane feed stream parameters modification suitable for oil-water separation for optimal performance. It was reported that the optimization of the operating parameter leads in the integrated membrane feed stream leads to the lower running cost of the oil-water filtration system and improved performance of the membrane (Ebrahimi et al., 2020; B. Zhu et al., 2018). The operating parameters reported to be playing an important role during oil-water separation, however reviewing their effects alone will not provide an adequate solution to optimize the membrane performance. Therefore, the investigation of operating conditions could assist in providing the understanding of membrane performance and, the better relation of the operating parameters and the surface of the integrated membrane feed stream.

4.4 Operating Conditions in the Integrated Membrane Feed Stream

The operating conditions in this literature review are pore sizes and the morphology of pore size distribution of the integrated membrane feed stream during oil-water separation. In recent, several investigations have been conducted on the pore sizes influence in the integrated membrane feed stream to improve the oil-water separation efficiency of the membrane. The pore sizes variation has been reported to be affecting the performance of the integrated membrane feed stream, either positively or negatively, significantly (Ezugbe & Rathilal, 2020; Jepsen et al., 2018). Moreover, the poor estimation of pore sizes may cause a high-temperature polarization effect and pressure drop in the feed stream of the integrated membrane system during oil-water separation, which leads to poor performance of the membrane (Elhady et al.,

2020). Several investigations were carried out to modify the pore sizes of the integrated membrane feed stream to optimize the oil-water separation efficiency.

For example, the feed stream efficiency of various pore sizes (150 µm and 50 µm) of the feed during the separation process in IMS was investigated and the results showed the high separation efficiency of oil-water to be 99% (Gebreslase, 2018). Which agreed with the results of the study of operational performance and durability of the integrated membrane feed stream during oil-water separation where also a high separation efficiency of (99.9%) was observed, reported that the ceramic membrane demonstrated superior durability towards harsh operations (Lu et al., 2018). In contrast, it was found that the permeate flux reduction is higher with an increased oil-water concentration, which the decline was caused by the membrane fouling and lead to poor oil-water separation (Qin et al., 2019; Zhao et al., 2020). Furthermore, the MF integrated membrane feed stream oil-water permeate flux was analyzed using the membrane pore size of 0.2 µm and showed the decline to permeate flux at about pseudo- steady-state ~10% of the initial value (Tanudjaja et al., 2019).

Although several studies showed that modifying the pore sizes distribution increases the permeate flux performance, however, some investigations show that the modification of the pore sizes beyond 15% of the axial stretching leads to the poor morphology of the pore sizes distribution at about 30% of pores as shown in figure 5 (Han et al., 2019). Therefore, it was reported that during the modification of the integrated membrane feed stream pores sizes the morphology of the pore size distribution should also be considered as it plays a role in the optimization of the oil-water permeate flux and rejection factor (B. Ma et al., 2019).

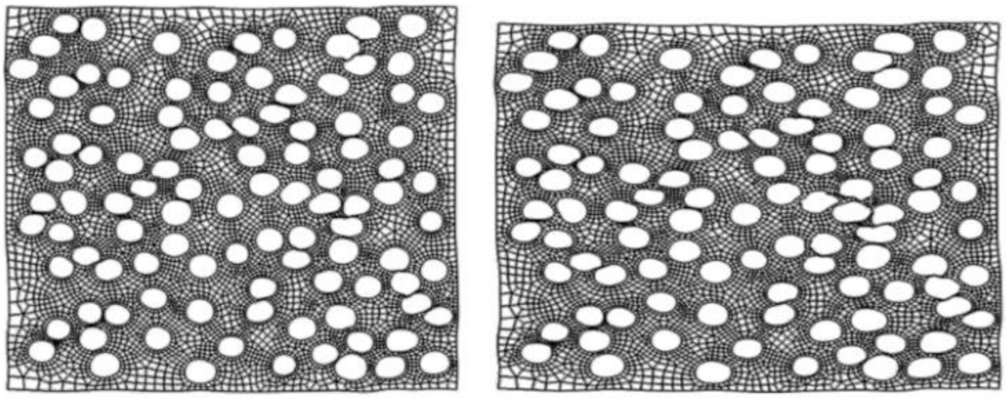

Figure 4: Schematic of the Stretched Integrated Membrane System Pore Sizes (E. Tummons et al., 2020).

4.5 Morphology of the Pore Sizes Distribution in the IMS Feed Stream

Using unsuitable operational conditions such as pore size, poor distribution of pore size morphology and poor wettability will hamper the efficiency of the membrane due to the decline to permeate flux caused by deficiency of oil-water separation in the integrated membrane feed stream (He et al., 2017). To date, there is not enough literature evidence showing the predictive models of the morphology of pore sizes distribution with respect to the feed streamflow. The main limitation reported on integrated membrane feed stream is that the uneven morphological distribution of pore sizes distribution as shown in figure 6 (Baig et al., 2020). Therefore, it is important to characterize the morphologies of pores for optimal oil-water separation in the integrated membrane feed stream. Since it was reported that the surface of the

membrane has a direct impact on the wettability of the membrane (Rong et al., 2018). In summary, the optimized morphology pore size distribution of the integrated membrane system could provide a better understanding of membrane wettability.

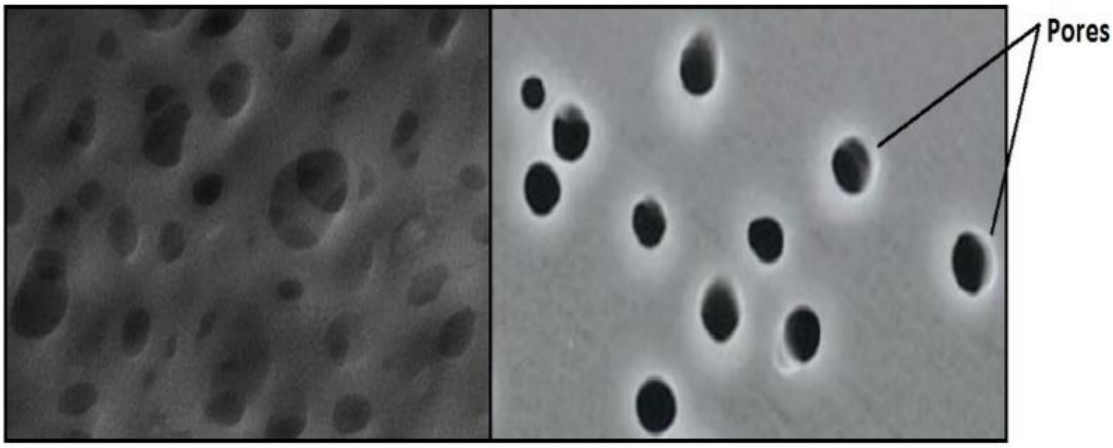

Figure 5: Schematic of Pore Size Distribution in the Integrated Membrane Feed Stream *(Venzke et al., 2018)*.

5. Critical Operating Parameters in the Integrated Membrane Feed Stream

The operating parameters that influence the performance of the integrated membrane feed stream during the oil-water separation process are found to be the feed stream flow rate, transmembrane pressure (TMP), crossflow velocity (CFV), feed temperature (T) (Salama, 2018c). The influence of the parameters in the integrated membrane system is measured in relation to the permeate flux during the oil-water separation to measure their influence in the permeate rejections (Borea et al., 2018; Monfared et al., 2016). The membrane performance is characterized mainly in terms of permeate flux and rejection efficiency (Samaei et al., 2018).

5.1 Model (I) Permeate Flux Mathematical Model

Model (I) is the permeate flux model that shows the relation of the feed stream of the integrated membrane to the permeate rejection which is permeate flux as shown in figure 7.

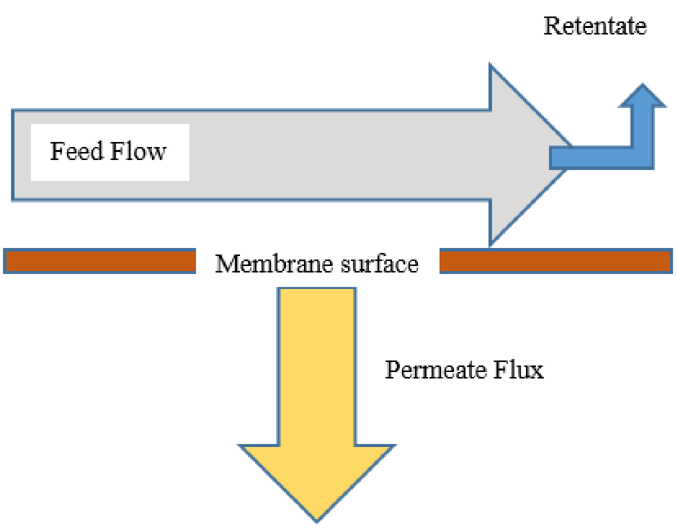

Figure 7: Demonstration of the Permeate Flux in the Integrated Membrane Feed Stream.

To date, several investigations have been carried out to investigate the influence of the feed stream operating parameters with respect to the performance of the membrane. Several mathematical models were developed and modified accordingly and compared for their optimal performance. Therefore, the feed stream of the integrated membrane system is characterized by developing the permeate flux models to estimate the permeate rejections in the membrane. And to optimize the performance of the membrane during oil-water separation. the model of permeate flux in the integrated membrane to be presented by J measured in $\mathrm{L\,m^{-2}h^{-1}}$, and is calculated from equation 4 (S. Huang et al., 2018; Shirazi et al., 2016a).

$$\mathrm{J} = {}^{\mathrm{V}}/_{\mathrm{A\Delta t}} \tag{4}$$

In this model 4 represents the permeate volume (L), A is the useful area of the membrane in $(\mathrm{m^2})$ and $\Delta\mathrm{t}$ denotes the processing period in (h). Equation 4 was mostly reported in the investigation of oil-water separation on the calculation of the permeate flux to investigate the membrane performance (Jia et al., 2018; Yanan Liu et al., 2017; Monfared et al., 2016). In contrast, the mass of a collected permeate ΔW was preferred instead of using the 4 which is the volume of oil that permeates through the membrane during the oil-water separation process (J. Zhu & Jin, 2017). This model was derived from Darcy's equation developed by Mulder and Mulder in 2010 given by equation 5 (Bolto et al., 2020; Wan et al., 2017).

$$\mathrm{J} = \frac{\Delta\mathrm{W}}{\Delta\mathrm{t}\times\mathrm{A}} \tag{5}$$

Moreover, the permeate flux mathematical model was further modified for the optimally integrated membrane feed stream during the oil-water separation by considering the effects of hydraulic resistance and the transmembrane pressure (Han et al., 2019). The mathematical model was found to be as shown by equation 6 (Lin et al., 2019; Z. Zhang et al., 2019).On Equation (6) the J_o represents the permeate flux of the membrane $(\mathrm{m^3/m^2.s})$, differential transmembrane pressure given by TMP in (Pa), and μ denotes the dynamic viscosity of the permeate solution in (Pa.s). In contrast, there are other operating factors reported which have the direct impact on the influence of the operating parameters during the oil-water separation. These parameters need to be considered during the analysis of the integrated membrane feed stream for optimising the permeate flux. These parameters are osmotic differential pressure across the membrane measured in (Pa), permeate flux resistance due to fouling given by $R_f(\mathrm{m^{-1}})$ and σ defines the reflection coefficient as represented by in equation 7 (J. Zhang et al., 2019).

$$J_o = \frac{\mathrm{TMP}}{\mu R_m} \tag{6}$$

$$J = \frac{TMP-\sigma\Delta\pi}{\mu(R_m+R_f)} \tag{7}$$

For the permeate flux to occur from the direction of the feed stream to the permeate direction, the membrane pressure exerted across the membrane must be greater than the osmotic pressure (S. Zhang et al., 2018). Therefore, the osmotic pressure can be computed by employing the van't Hoff's equation as shown in equation 8 (Yi Liu et al., 2020). Where i defines the van't Hoff's factor and is a unitless value, R represent the ideal gas constant in $(\mathrm{J/mol.K})$, T in the oil-water feed temperature (K), C_m (mol/L) being the concentration of oil-water emulsions in the immediate vicinity of the surface of membrane and C_p denotes the oil/water concentration in the permeate.

$$\Delta\pi = i * R * T * (C_m - C_p) \tag{8}$$

5.2 Model (II) Models Developed to Predict the Effects of Membrane Fouling in the Integrated Membrane Feed Stream.

The membrane fouling is a process of the undesirable material (e.g., oil) piling up on the feed stream surface of the integrated membrane system such as flake during oil-water separation. To date, membrane fouling is considered the major problem in the feed stream of integrated membrane system which affects the oil-water separation process negatively by blocking the membrane pores to reduce the permeate flux as demonstrated by figure 8(Hubadillah et al., 2018; J. Liu et al., 2016; Ngang et al., 2017; Salama, Zoubeik, et al., 2018).

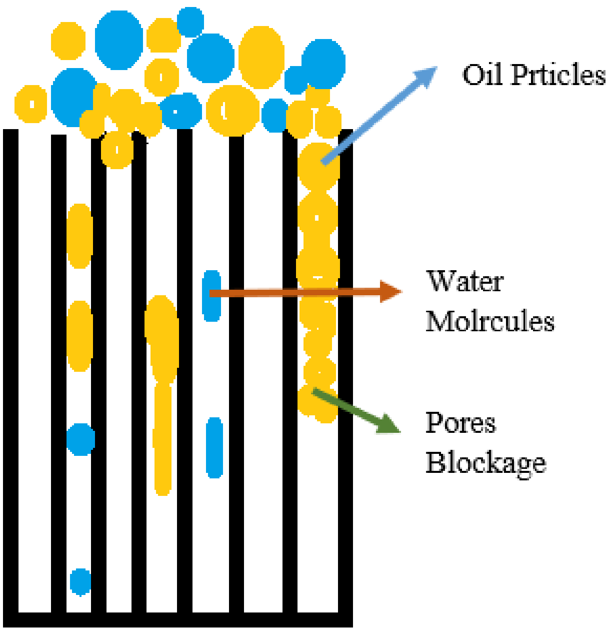

Figure 8: Demonstration of Pores Blockage in the Integrated Membrane Feed Stream through Oil-Water Emulsions.

Several membrane fouling resistance models were developed to predict the fouling resistance in the integrated membrane feed stream. The fouling resistance mathematical model were developed by taking into consideration the membrane with pure water to remove any residual particle on the membrane surface (C. Li et al., 2020; W. Liu et al., 2020).The equation was modified by subtracting the resistance of the clean membrane before filtration and obtained equation 9 (Shirazi et al., 2016b). Where R_f is a time-dependent membrane fouling resistance (m^{-1}), R_m is the intrinsic membrane resistance (m^{-1}),R_t being the total resistance in the integrated membrane feed stream and J_f is the water flux of the fouled membrane before rinsing $(\mathrm{L.h^{-1}m^{2}})$.Instead, the model for both reversable and irreversible foiling resistance is presented by equation 10 and 11 (Kalla, 2021; J. Li et al., 2018; Woo et al., 2018). Where J_R represents the water flux of the cleaned membrane, J_o being the water flux at an initial state, R_r is the reversable fouling resistance and R_{ir} is the irreversible fouling resistance.

$$R_f = R_t - R_m = \frac{TMP}{\mu \times J_f} - R_m \tag{9}$$

$$R_r = \frac{J_R - J_P}{J_o} \times 100 \tag{10}$$

$$R_{ir} = \frac{J_O - J_R}{J_O} \times 100 \tag{11}$$

Later, the further modifications were on the fouling resistance model which contradicts the model developed 9 (Tin et al., 2017). Where, on equation 8, instead of subtracting the effects of the clean membrane, the addition of all membrane resistance taking place during oil-water separation in the integrated membrane feed stream was considered. In general, this model of summing the total resistance in the membrane is defined to be resistance-in-series given by equation 12 (Rong et al., 2018). Equation 12 is a method used to quantify the irreversible and reversible membrane fouling during the oil-water separation in the integrated membrane feed stream. Where ΔP is the driven pressure, μ defines the viscosity, R_{rev} is the hydraulic resistance due to reversible, R_m is the hydraulic resistance of clean membrane, and R_{irrev} represents the irreversible membrane fouling.

$$J = \frac{\Delta P}{\mu(R_m + R_{rev} + R_{irrev})} \tag{12}$$

Therefore, equation 12 provides a better fouling estimation in the integrated membrane system as compared to equation 11, because it considers all the hydraulic fouling which takes place in the membrane during the oil-water separation process (Liao et al., 2017). For constant pressure operations a constant reversible and irreversible membrane fouling may be reached if the equilibrium between the accumulation of foulants and their removal away is reached. As indicated, pressure applied across the membrane plays an important role during the oil-water separation and in the reduction of membrane fouling. Therefore, the pressure effects on the integrated membrane feed stream during oil-water separation must be estimated for the optimal membrane performance.

5.2.1 The Transmembrane Pressure Effects on the Performance of the Integrated Membrane Feed Stream

Transmembrane pressure is elaborated as the pressure applied across the membrane, for the oil-water separation to take place this pressure must be greater than the osmotic pressure (Baig et al., 2020). Thetransmembrane pressure model across the integrated membrane feed stream takes into consideration the pressure on the feed side, retentate pressure and filtrate pressure as P_{feed}(bar), $P_{retentate}$(bar),$P_{filtate}$(bar), respectively as presented in equation 13 (He et al., 2017).

$$TMP = \frac{P_{feed} + P_{retentate}}{2} - P_{filtate} \tag{13}$$

In contrast, the transmembrane pressure ΔP (bar) model developed in equation 14, considered only the effects of feed pressure P_{feed} (bar) and permeate pressure $P_{permeate}$(bar) without considering the effects of the retentate pressure. Moreover, equation 16 took into consideration considered the effects of the osmotic pressure (Δπ) when deriving the net driven pressure (NDP) across the membrane which the models are given below respectively by equations 14, 15 and 16 (Eykens et al., 2017; Islam et al., 2017; B. Ma et al., 2019; E. Tummons et al., 2020).

$$\Delta P = P_{feed} - P_{permeate} \tag{14}$$

$$\Delta\pi = \pi - \pi_p \tag{15}$$

$$NDP = \Delta P - \Delta\pi_m \tag{16}$$

In the integrated membrane feed stream, the permeate flux is found to be directly proportional to transmembrane pressure. In comparison, equation 13 was used to obtain the results in figure 9 a), where the effects of transmembrane pressure in the integrated membrane feed stream were investigated in relation to permeate flux. Similarly, Equation 16 was

adopted in figure 9 b) for the investigation of optimal permeate flux through the analysis of pressure influence on the permeate rejections. Figure 9 serves as an evidence to the statement made that the pressure applied across the integrated membrane feed stream is directly proportional to the permeate flux during the oil-water separation (Y. Yu et al., 2016).

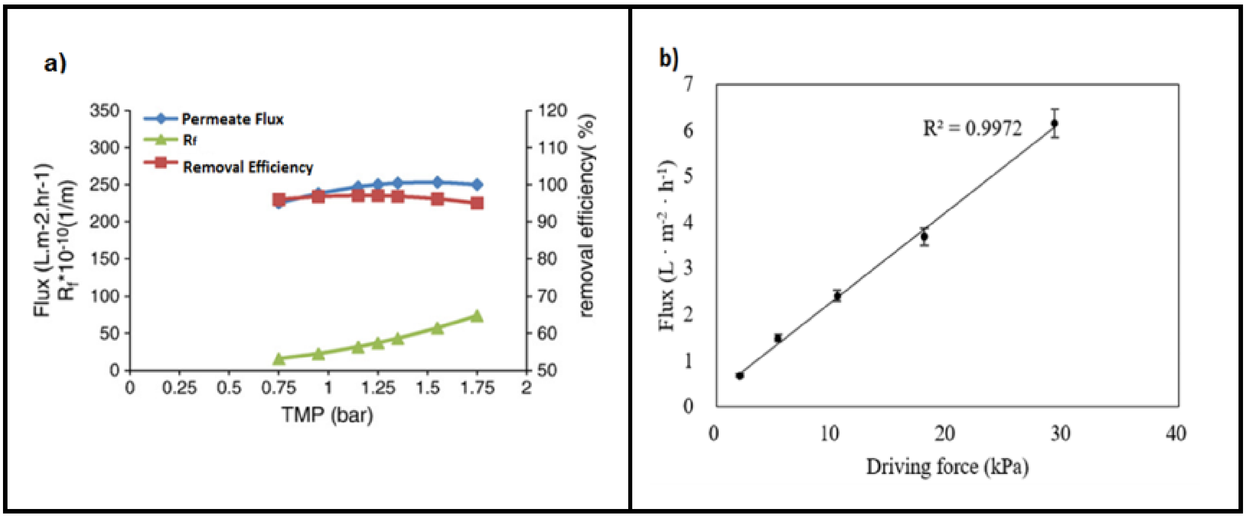

Figure 9: Comparison of Pressure Influence on Permeate Flux *(Yang et al., 2016; Y. Yu et al., 2016)*.

6. EXPERIMENTAL INVESTIGATIONS FOR POROSITY, PERMEATE FLUX AND OIL REJECTIONS IN THE INTEGRATED MEMBRANE FEED STREAM

The permeate flux in the integrated membrane feed stream of the MF was optimised by applying 0.1 bar hydraulic pressure through varying the feed stream concentration on the average pore size 40 nm membrane during the oil-water separation process using the experimental set up in figure 10 (Lu et al., 2018). The permeate flux was estimated from equation 1, which is commonly used in several studies and well-known rejection factor equation 2 (Qin et al., 2019; Raza et al., 2019).In Equation (1), the J_o represents the permeate flux of the membrane $(m^3/m^2.s)$, transmembrane pressure differential given by TMP in (Pa), and μ denotes the dynamic viscosity of the permeate solution in (Pa.s). Represents the oil rejection to ratio of permeate concentration (C_{perm}) and feed concentration (C_{feed}) as shown on equation 2.

$$J_o = \frac{TMP}{\mu R_m} \quad (1)$$

$$R = \frac{C_{feed} - C_{perm}}{C_{feed}} \times 100 \quad (2)$$

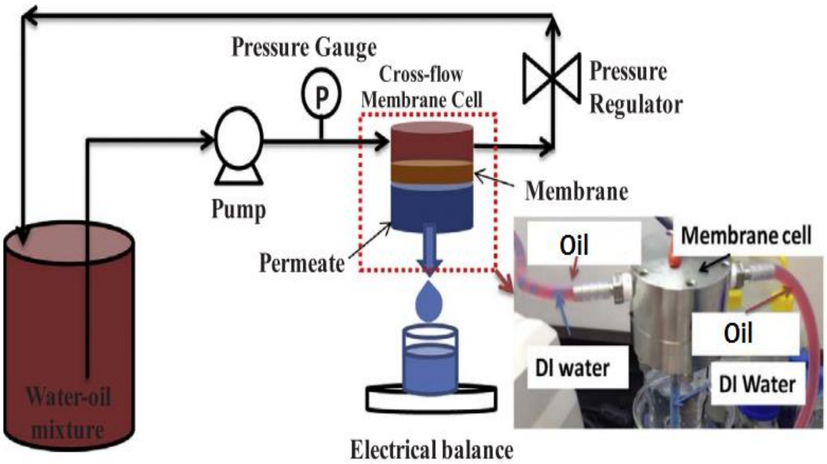

Figure 6: Schematic of Oil/water Separation Experimental set up for Crossflow Membrane*(Tanudjaja et al., 2019; Zhao et al., 2020)*

Therefore, the results in figure 11 were observed during the examination of oil-water separation in the integrated membrane feed stream for the investigation of the membrane performance through the assessment of the permeate flux and oil rejection factor. This study demonstrated a good correlation between the developed models 6 and 8 in sub-section one, like equations 1 and 2, with the experimental examinations. Where the oil-water separation efficiency was estimated to be 99%. In contrast, since several studies note that permeate flux depends on feed composition, therefore in the current study it was revealed that when increasing the water content in oil, the oil flux decreases (Tanudjaja et al., 2019; Zhao et al., 2020).

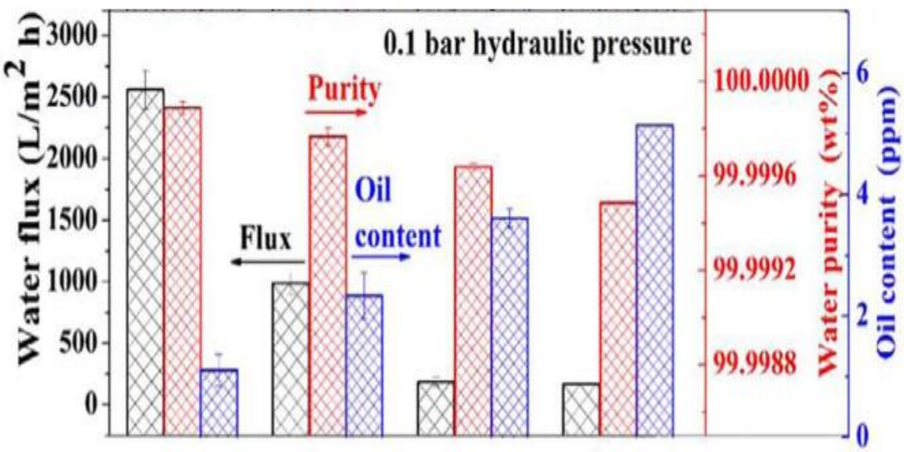

Figure 7: Schematic of Water Flux and Oil Content Produced by Experimental set up foC Cross flow Membrane(Tanne et al., 2019)

6. CONCLUSIONS

In conclusion, integrated membrane systems have become a promising technology for oil-water separation with a high separation efficiency at low costs (Venzke et al., 2018). Even though the integrated membrane system has been remarked as the superior oil-water separation technology, its feed stream is still prone to membrane fouling (Guo et al., 2018). Up to date, membrane fouling is considered the worldwide challenge which the integrated membrane system is facing, which

causes the permeate flux decline and leads to the poor performance of the membrane (Brown & Bhushan, 2015). Several studies have considered different approaches to overcome the integrated membrane fouling, to optimize the performance of the membrane. Such as optimizing the membrane performance by developing the mathematical models concerning the operating parameter, for example, the transmembrane pressure (TMP), crossflow velocity (CFV), feed concentration, etc (Ahmad et al., 2015; Salama, Ibrahim, et al., 2018). And other studies focused on the relation of the theoretical model to the experimental test set up to achieve the optimal integrated membrane performance. Even though some of these existing mathematical models and experimental setup exhibited improved membrane performance. In contrast, some of the developed techniques also showed limitations due to not considering all existing physical parameters which have a direct impact on the permeate flux during the oil-water separation. The major factor which is affecting the performance of the integrated membrane system was reported to be not well-characterized pore size morphology. Which the characterization of the poor size in the integrated membrane feed stream will serve as one of the predictive tools to membrane fouling and permeate flux for optimal membrane performance. The mathematical model needs further modification for the optimal oil-water separation efficiency.

FUTURE SCOPE

The improvement of the integrated membrane feed stream is considered to have a direct influence on optimizing the performance of the membrane system during the oil-water separation at low cost and high separation efficiency. This review focused on the optimization of the integrated membrane feed stream through both mathematical models and experimental analysis. The consideration of an integrated membrane system becomes limited, due to its feed stream fouling which causes the permeate flux decline and poor oil-water separation. Several researchers reported that the mathematical models and experimental analysis of the integrated membrane feed stream need to be further modified to achieve optimal performance. Identified future scope for optimizing the integrated membrane feed stream are as follows:

- Modification ofthe integrated membrane feed stream mathematical models concerning the membrane surface, to achieve the optimal membrane performance during oil-water separation.
- Characterization of pore sizes morphology distribution is a promising predictive model for membrane fouling, which will minimize the integrated membrane feed stream fouling and improve the membrane wettability and permeate flux.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest in the manuscripts between authors and involved institutions.

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